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Mafic Dikes of Northeastern Massachusetts

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INTRODUCTION

Over the past decade, interest in the mafic dikes of eastern North America has increased, beginning with the regional reconnaissance geochemical study of Mesozoic dolerite dikes by Weigand and Ragland (1970). McHone (1978), in a study of lamprophyre dikes of New England, also compiled the available chemical, field, and age data for northern New England Mesozoic mafic dikes in general. Only two dikes from northeastern Massachusetts are included in that compilation. Previous work in this area and eastern Massachusetts in general has been mainly field oriented with a limited amount of chemical and petrographic study (Shaler, 1889; Washington, 1899, Emerson, 1917; Wilson, 1901; LaForge, 1932; Bell, 1948; Skehan, 1975; Billings, 1976; Dennen, 1976; Koch, 1978; Ross, 1981). Emerson (1917) included a few chemical analysis including 3 of the Medford dike. Dennen (1951) reported partial major element chemical analyses of the Medford diabase dike and a diabase dike from Nahant as part of an investigation of chemical changes across igneous contacts. To date, a detailed, systematic field and petrologic investigation of the mafic dikes in this area has not been conducted. The present study was begun in 1979 (some sampling was done in 1970-72) as an initial step toward producing detailed field, petrographic and geochemical information for the mafic dikes in the area.

From Boston north to Cape Ann, hundreds of mafic dikes intrude rocks that range in age from Precambrian to Carboniferous (?). Most of the dikes are generally regarded as Mesozoic but some may be as old as Precambrian. Four whole rock K-Ar ages of diabase dikes in the area range from 254 to 334±15m.y. (Zartman and others, 1970). Only 2 dikes dated since 1970 yield Mesozoic K-Ar ages and most minimum ages fall between 300 and 350 m.y. (H.W. Krueger, unpublished data).

MAFIC DIKE PETROGRAPHIC TYPES

At least 5 major petrographic varieties and 6 subvarieties have been recognized among the 46 dikes studied so far. Three of the main varieties are at present, represented by a single dike each. The majority of the dikes can be categorized as diabases (i.e. altered dolerites) and dolerites with the distinction based on the degree of sausuritization of plagioclase, uralitization of clinopyroxene (primarily augite), alteration of olivine, and relative abundances of other secondary phases (mainly chlorite, epidote, and carbonate). The degree of alteration in the dolerites ranges from nearly none to moderate in which uralitized margins account for less than about 50 percent of the volume of individual pyroxene grains, and twinning is still clearly visible in sausuritized plagioclase grains. In the diabases, the degree of alteration ranges from the maximum described above for dolerites to virtually total alteration of the essential minerals. Chlorite (often pennine) and epidote are far more abundant in the diabases (Table 1).

Diabases

The 22 diabase dikes studied can be further broken down into four petrographic subvarities: 1) 10 aphyric, 2) 3 aphyric with altered olivine 3) 5 plagioclase phyric $\pm$ minor-biotite, and 4) 2 plagioclase-phyric with altered olvine. Three aphyric diabases at Pine Hill contain brown amphibole (uralite). Representative modal analyses are shown in Table 1. Aphyric samples and groundmasses of phyric diabases tend to be fine- to medium-grained, equigranular and typically intergranular. Ophitic and subophitic textures are well-developed toward the centers of thicker dikes. Microporphyritic texture is typical of chilled dike margins and also in groundmasses of some phyric dikes. Glommeroporphyritic clusters of plagioclase phenocrysts and microphenocrysts are also fairly common (most plagioclase = andesine-labradorite).

Dolerites

The 19 dolerite dikes can be grouped into the following petrographic subvarities: 1) 9 are aphyric, 2) 4 areplagioclase-phyric, and 3) 5 aphyric and 1 plaioclase-phyric dike contains what appears to be subhedral to euhedral olivine altered to chlorite and magnetite $\pm$ calcite. Textures are as described above for the diabases with ophitic and subophitic textures generally better developed and more common. Plagioglcase phenocrysts tend to be smaller and less abundant. Representative modal analyses are shown in Table 2. Most of the plagioclase is andesine to labradorite.

Megacryst-rich Diabase

Plagioclase megacryst-rich diabase dike from Rockport has been examined and constitutes a petrographic type of its own. The plagioclase megacrysts increase in size and abundance toward the center of the dike where they attain a maximum length of at least 9.2 cm and account for approximately 35 volume percent of the rock (megascopically). Plagioclase phenocrysts and megacrysts make up as much as 53 percent of the mode (Table 1). The anorthite content of the phenocryst cores decrease from about An49 at the dike margin to An40 near its center. This dike contains more biotite than any other dike examined (Table 1).

Lamprophyres

Hyalo-monchiquite

A lamprophyre dike (hyalo-monchiquite) has been examined from Pine Hill and its modal analysis is shown in Table 1. Microphenocrysts of kaersutite and what appears to be a ferromagnesian mineral (olivine or pyroxene) completely altered to chlorite and magnetite (the latter along relic fractures) are set in a groundmass of clear to brownish glass and small microlites. The microlites consists of kaersutite, fresh augite and an opaque accessory mineral (probably magnetite). Both the Kaersutite and augite microlites are elongate prismatic grains. Small ocelli of analcime, kaersutite, and opaques are present as are irregular-shaped amygdales filled with calcite and zeolite.

Camptonite

An unusual camptonite dike containing abundant megacrysts, xenocrysts, and xenoliths was recently exposed in the subway tunnel being excavated beneath Porter Square in Cambridge. The dike was mapped by J. Chamness and R. Dill of Haley and Aldrich, Inc. and a large number of samples collected by J. Chamness have been provided to supplement the four samples collected by the author. The dike trends N15^{o} to 20^{o}E, is vertical, and has a maximum thickness of about 2.4 meters. Handspecimens will be brought on trip.

The plagioclase (An40) of the host lamprophyre occurs as late-forming, anhedral, lath-shaped grains riddled with euhedral poikilitic inclusions of augite, altered olivine, kaersutite, biotite, apatite, and opaques. These minerals also fill interstices between plagioclase laths giving the rock an intergranular texture. The plagioclase is fresh in contrast to the feldspar xenocrysts which are more sericitized.

The dike margin is aphanitic and free of xenoliths and xenocrysts within about 2.5 centimeters of the contact. Microcline and oligoclase xenocrysts begin to appear and become larger and more abundant between 5 and 9 cm of the dike margin where phenocrysts of biotite and amphibole (kaersutite ?) and small xenoliths also first start to occur. Locally between about 9 and 20 cm of the dike margin, feldspar xenocrysts up to about 4 cm long show marked flow alignment parallel to the dike contact. The xenoliths, xenocrysts, and megacrysts all increase markedly in size and abundance and the groundmass coarsens to become fine-grained at the center of the dike. Euhedral Kaersutite megacrysts of at least 8.0 cm length, biotites up to at least 5.5 cm in diameter, and plagioclase xenocrysts up to at least 7.5 cm in length are common within the central portion of the dike. Many of the feldspars are shattered and, when viewed in thin section, both microcline and oligoclase are embayed and corroded by the groundmass which strongly suggests they are xenocrysts and not megacrysts.

The xenoliths are angular up to at least 16 cm in diameter, and lack any megascopically visible reaction features at their margins. Rock types represented include pink medium- to coar-grained granitoid, (some resemble Dedham Granodorite) pink, medium-grained, garnetiferous quartzo-feldpathic gneiss, Cambridge Argillite, felsite (Lynn Volcanics ?), gray, garnetiferous, augite-bearing granulite, and what appears to be an ultramafic rock. Except for the Cambridge Argillite, possible Dedham Granodiorite, and the felsite, none of the xenoliths examined megascopically resemble rocks exposed at the surface in the greater Boston area, and some appear to be of deep crustal and, perhaps, mantle origin.

Similar dikes in southwestern Rhode Island have been described in detail (Leavy and Hermes, 1977) and it is not inconceivable that the Porter Square dike is related to that series although the host rocks are chemically quite dissimilar. LaForge (1932) briefly described 2 "inclusion-bearing dikes" trending between due north and N25^{o}E that cut Cambridge "slate" in the old Mystic Quarry in Somerville. Inclusions of Dedham Granodiorite and Lynn Volcanics and pieces of minerals and rocks not found at the surface in the Boston area are present (LaForge, 1932). This dike has not yet been observed by the author but could easily be a northeast extension of the dike beneath Porter Square.

Medford Dolerite Dike

The Medford dike attains a thickness of 122 meters at Pine Hill, Medford and is petrographically distinct from the other dike groups (Table 1). It has traditionally been considered a diabase (Wilson, 1901; LaForge, 1932) but Skehan (1975) refers to it as a diorite. Based on its plagioclase anorthite content (An70 cores, An29 rims) an SiO_2 content less than 52% (Table 2), ophitic to subophitic texture, and relatively unaltered mineralogy, it is a biotite-rich dolerite containing minor quartz and granophyre (using the nomenclature of this report). A modal analysis of one sample from the interior of the dike at Pine Hill is listed in Table 1 and a chemical analysis in Table 2.

Dike Chemistry

Nine new major and partial trace element analyses of 7 selected dikes suggests a broad range of compositions are represented (Table 2). The mean of 3 Medford dike analysis (Emerson, 1917) are also listed for comparison. Alkali-silica plots using the alkaline-tholeiite discriminant of Irvine and Baragar (1971) indicates 6 dikes are alkaline and 2 are tholeiitic. The alkaline dikes can tentatively be subdivided into 4 chemical types: 1) two plagioclase-phyric diabases have relatively low SiO_2 and CaO and high Al_2O_3 and TiO_2 (samples 107 & 127Table 2), 2) one aphyric doloerite has relatively high SiO_2, CaO, TiO_2, and P_2O_5, and low Al_2O_3 (sample 51 Table 2), 3) the groundmass of the xenolith and xenocryst-rich camptonite has low SiO_2 and TiO_2, very low CaO, and high Al_2O_3, Zr, Sr, and Rb (sample 19 Table 2), and 4) the plagioclase megacryst-rich diabase is highest in SiO_2, Al_2O_3, and total alkalis (1 and 9, Table 2). The Medford dike may be a fifth alkaline type having the lowest TiO_2 and highest Al_2O_3 (Table 2) but new analyses are in progress.

The two tholeiitic dolerites form two chemical types on the basis of high and low TiO_2 contents (nos. 112 and 13, Table 2). The possible effects of alteration on dike chemistry could account for some of the variation detected. Decreases in CaO, MgO, and SiO_2, and increases in Fe^{3+}, Na_2O, K_2O, and H_2O have been documented for Mesozoic basalts of the Newark and Hartford Basins and attributed to possible interaction of basalt with sea-water at low temperatures (Puffer and others, 1981).

Dike Ages

Whole-rock K-Ar ages have been published (Zartman and others, 1970) for four "basalt dikes" between Boston and Rockport which have not yet been sampled as part of this study. Their ages range between 254 and 334 $\pm$ 15 m.y. Four of the dikes included in the present study have also been dated (K-Ar whole-rock) by H.W. Krueger of Geochron Laboratories, Inc. and are as follows: 383 $\pm$ 23 m.y. and 299 $\pm$ 21 m.y. for two olivine-bearing dolerites at Stop 2, Saugus ; 202 $\pm$ 8 m.y. for the camptonite at Porter Square, Cambridge, and 190 $\pm$ m.y. for the Medford dike at Pine Hill, Medford (Stop 1) (H.W. Krueger, personal communication, 1981).

LaForge (1932) grouped the mafic dikes in the Boston area into four sets on the basis of their trends and cross-cutting relationships: 1) an older east-west set found only in pre-Carboniferous rocks south of Boston and are scarce; 2) a younger (late Carboniferous) east-west set (N. 60° W to S. 75°W) which cut all formations in the area, are up to 152 m thick, commonly porphyritic and includes sills up to 9 m thick; 3) a northwest-southeast set which is locally cut by the younger east-west set but elsewhere occur as offshoots from it; 4) a north-south set (due to north to N25°E) of olivine diabases (Triassic) cutting all other units and with a maximum thickness of 12 meters. LaForge (1932) treated the Medford dike as a Triassic unit by itself.

All but three of the dikes studied so far can be placed in sets 2 through 4 above. Five aphyric diabases, 6 aphyric dolerites, and 3 plagioclase-phyric dolerites have strikes within the range of LaForge's younger east-west set. Seven aphyric diabases, 5 plagioclase-phyric diabases, 1 plagioclase-phyric dolerite and the plagioclase megacryst-rich diabase have northwest-southeast trends. Three aphyric diabases, 1 plagioclase-phyric diabase, 2 aphyric dolerites, 2 lamprophyres, and the Medford diabase dike fall within the range of LaForge's (1932) north-south set. A third lamprophyre recently sampled with G. McHone at Chubb Point at the south end of Manchester (originally mapped by Shaler, 1899) trends N15°E and 2 north-south trending dikes mapped as lamprophyres by Wilson (1901) are present at Pine Hill, Medford but have not yet been verified by thin section analysis. Three aphyric dolerites have northeast-southwest trends and cannot be grouped into any of LaForge's sets.

Of the chemically analyzed dikes, the two tholeiitic, aphyric dolerites have northeast trends; one Siluro-Devonian, alkaline, aphyric dolerite trends N65°W; the camptonite trends about N15°E (J. Chamness, personal communication); the alkaline Medford dolerite dike has an average trend of N 19°E (LaForge, 1932); and the alkaline, plagioclase megacryst-rich diabase dike at Rockport trends N 14°W.

At the south end of Marblehead neck (Stop 5) a northeast trending aphyric, tholeiitic dolerite and 2 aphyric diabases (NE and due north trends) are cut by an alkaline, plagioclase-phyric, northwest trending diabase which in turn is cut by another thinner alkaline, plagioclase-phyric, northwest trending diabase (Ross, 1981). At this locality then, the northwest trending porphyritic diabases are the youngest units. It is clear from evidence at this locality that assuming altered dikes (diabases) to be older in general than unaltered dikes (dolerites) is not valid.

A tentative listing by relative ages from oldest to youngest for dikes in the area of the present study would be as follows: aphyric, northeast to east-trending diabases; aphyric, northeast-trending, tholeiitic dolerite; two sets of plagioclase-phyric, northwest trending, alkaline diabases; aphyric, east-west to northwest trending, tholeiitic dolerite; the alkaline, Medford dolerite; and north to northeast trending lamprophyres. More petrographic, chemical, and field data are required in addition to age dating before a more definite scheme of relative and absolute ages can be established.

TABLE 1. Representative modal analyses of mafic dikes, northeastern Massachusetts[1]

Sample Number[2]	51	112	13	127	107	111	MED	9	20	221
Total Plagioclase	61.6	55.3	49.5	44.1	58.5	61.3	67.5	75.7	61.1	-
Phenocrysts	2.7	-	1.7	4.5	trace	-	-	53.1	-	-
Total Augite	24.7	37.0	39.4	39.9	21.0	25.7	18.2	12.8	20.2	4.2
Uralitized	3.8	26.0	4.3	36.0	17.0	22.2	1.8	11.1	13.1	-
Opaque Accessories	8.7	5.8	7.1	4.5	8.9	7.9	2.5	3.1	12.0	13.4
Nonopaque Access.[3]	2.5	0.9	1.0	-	1.3	0.1	1.9	0.6	1.1	-
Altered Olivine	-	trace	trace	-	-	trace	-	-	1.4	2.4
Biotite	-	-	0.2	-	-	-	6.1	7.3	4.0	-
Kaersutite	-	-	-	-	-	-	-	-	-	32.0
Ocelli	-	-	-	-	-	-	-	-	-	7.4
Glass/mesostasis	-	-	-	-	-	-	-	-	-	40.6
Other Secondary	2.5	1.0	1.0	2.3	10.3	5.0	1.8	0.5	0.1	-
Chlorite	2.5	-	1.0	2.3	10.3	2.1	0.8	0.5	0.1	-
Epidote	-	1.0	-	0.3	-	2.9	0.5	-	-	-
Carbonate	trace	-	-	-	trace	-	0.5	-	-	trace

[1]Modal analyses based on 1000 points counted per thin section.
[2]See Table 2 for sample localities except the following: 111, aphyric diabase, Marblehead Neck (Dike C, Fig. 4); 221, hyalo-monchiquite, Pine Hill, Medford (dike 8, Fig. 2); 20 is coarser sample from interior of same dike as sample 19, Table 2.
[3]Typical accessories are apatite ± quartz

TABLE 2. Chemical analyses of mafic dikes, northeastern Massachusetts[1]

Samples[2]	107	127	112	13	51	1	9	19	MED
SiO_2	44.7	45.1	48.1	47.5	47.2	49.1	49.0	46.5	46.82
Al_2O_3	16.2	16.1	14.9	13.5	14.3	14.6	17.9	16.0	20.46
CaO	8.54	9.38	11.1	10.6	9.41	6.90	7.73	4.46	7.40
MgO	4.96	6.03	5.23	2.54	4.26	2.53	2.54	4.28	3.13
Na_2O	3.35	2.32	2.58	2.81	2.71	4.28	4.35	3.94	3.17
K_2O	1.09	1.80	0.60	0.65	1.56	2.69	1.97	2.21	2.10
FeO	14.0	11.6	11.5	12.9	12.6	11.7	10.6	12.2	13.09
MnO	0.21	0.18	0.20	0.22	0.24	0.26	0.23	0.14	0.73
TiO_2	3.09	3.03	2.07	3.03	3.14	2.42	2.27	1.99	0.33
P_2O_5	0.62	0.38	0.40	0.44	1.31	1.28	1.31	1.02	0.69
L.O.I.	2.39	2.47	1.62	1.77	2.47	1.08	1.00	4.85	2.35
Trace elements (ppm)									
Cr	30	170	140	230	50	40	20	80	
Zr	200	160	190	170	230	340	290	460	
Sr	630	620	600	360	580	620	840	1100	
Rb	30	40	10	80	20	50	10	100	

[1]XRF analyses by X-ray Assay Laboratories Ltd.
[2]Sample locations and dike types:

107: dike B, Marblehead Neck; plagioclase-phyric diabase; alkaline.
127: dike I, Marblehead Neck; plagioclase-phyric diabase; alkaline.
112: dike D, Marblehead Neck: aphyric dolerite; tholeiitic.
13: dike along Rte. 93 near Pine Hill, Medford; mean of two analyses; aphyric dolerite; tholeiitic.
51: dike 7 behind K-Mart, Saugus: aphyric dolerite; alkaline.
1: Rockport Headlands; plagioclase megacryst-rich diabase, contact.
9: Center of dike 1 above; alkaline.
19: Porter Square, Cambridge subway tunnel; xenolith-rich camptonite.
MED: Medford dike at Pine Hill, Medford (Emerson, 1917); mean of three.

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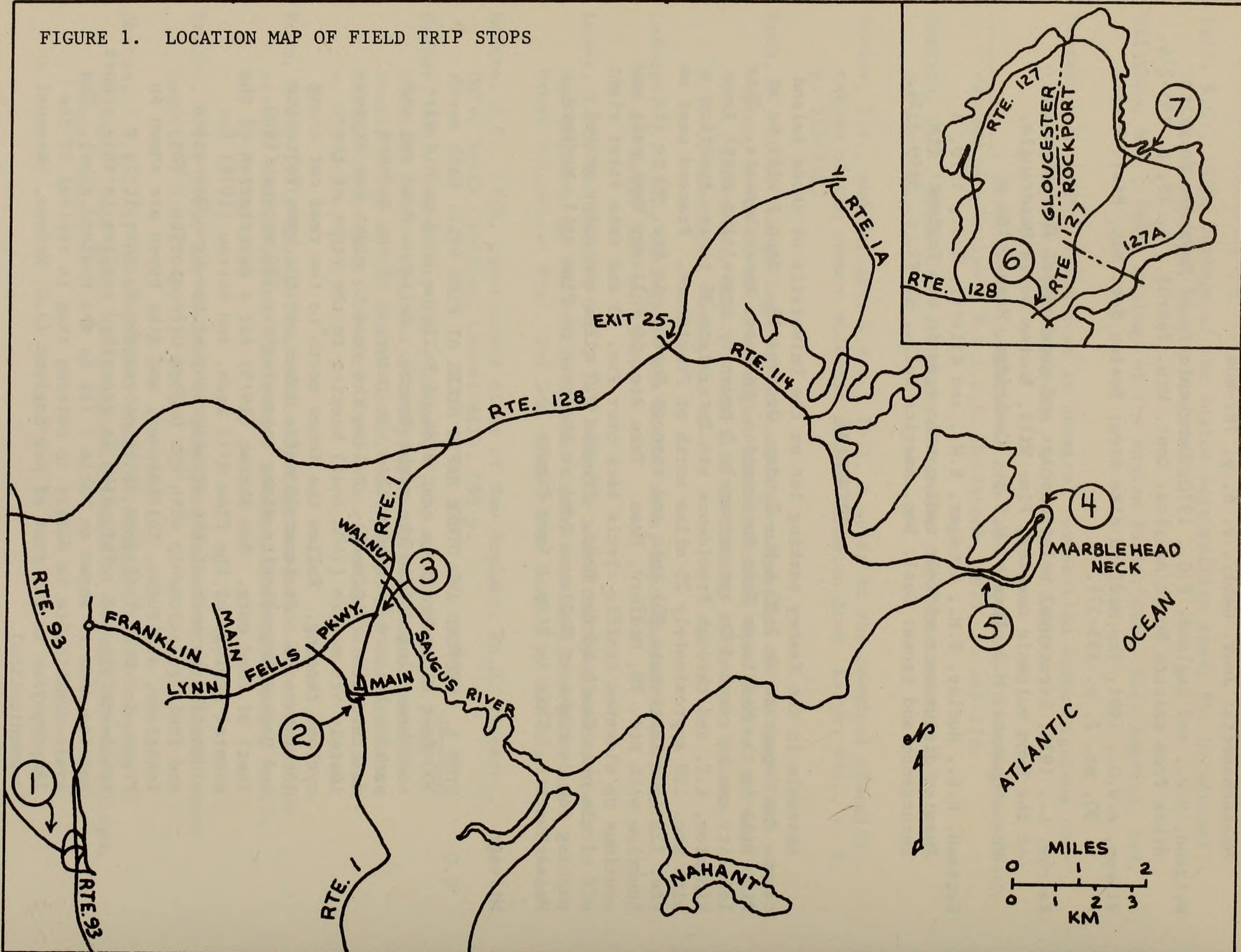
ITINERARY

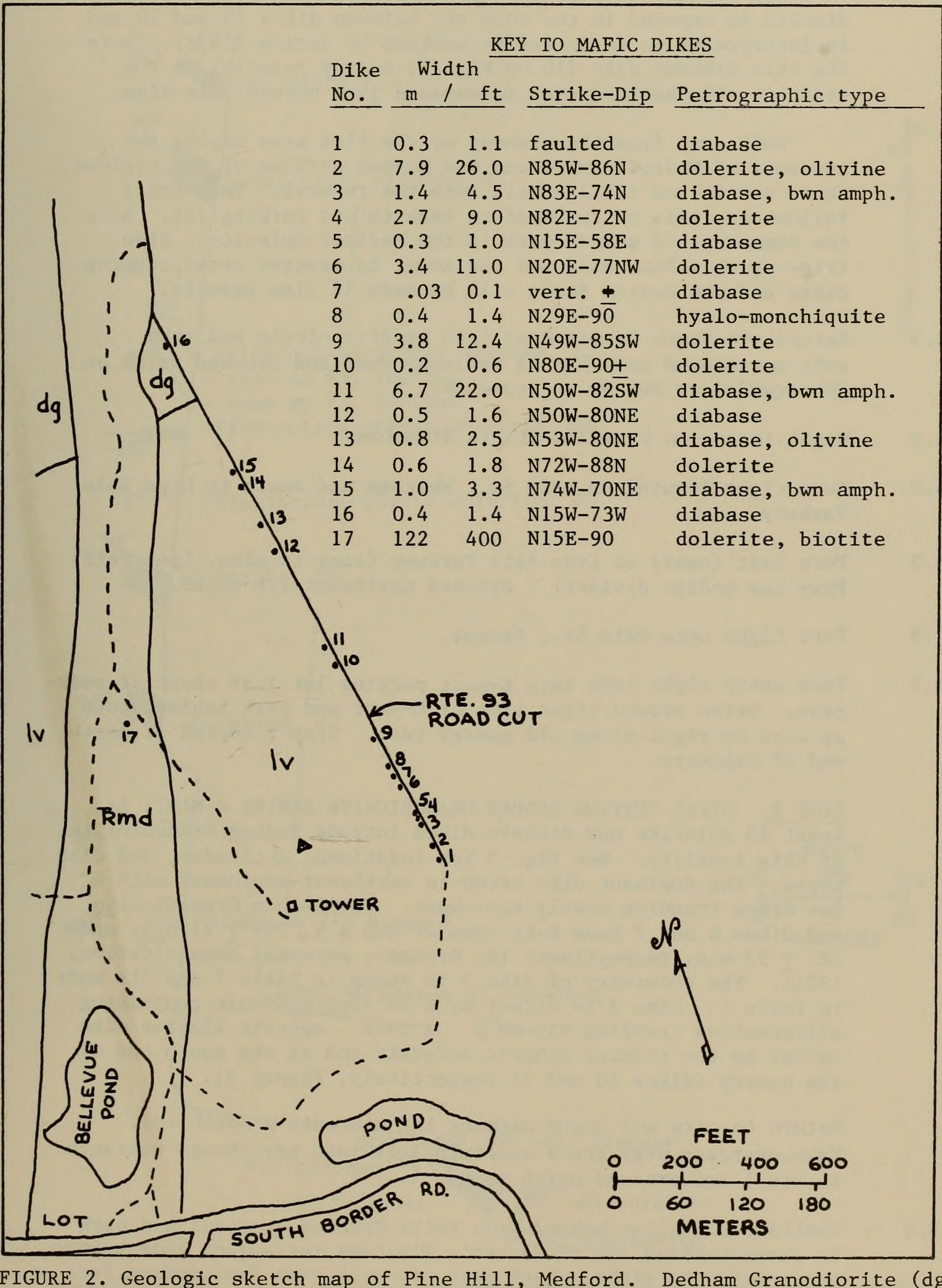
Assemble in the Keeney parking lot on the University of Rhode Island campus for departure at 7:30 A.M., Sunday, October 18. Stop 1 will be at Pine Hill in the Middlesex Fels Reservation, Medford, Massachusetts. This locality can be reached in approximately 3 hours by travelling north from Kingston, R.I. and through Providence via Interstate 95 to its junction with Rte. 128 approximately 25 miles north of Providence. Proceed east on Rte. 128 (and Interstate 93) into and through Boston via Rte. 93 to its junction with Rte. 28, Medford, Mass. Take Rte. 28 Fellsway West exit and continue on elevated traffic circle back over Rte. 93 and take first right off circle onto South Border Road. Proceed 0.3 miles and enter gravel parking lot on right at Bellevue Pond at the base of Pine Hill, Medford, Massachusetts. This is Stop 1 (see Figure 1).

Mileage

0.0 STOP 1. MEDFORD AND OTHER MAFIC DIKES AT PINE HILL: Walk north 300 feet along trail on east side of Bellevue Pond to old dirt road branching off to the right (east). Bellevue Pond and the parking lot are located within the interior of the Medford dolerite dike (Figure 2). Follow the road to right for approximately 425 meters (1400 feet) keeping to the right of the cyclone fencing. Follow the fence north to the road cut along Interstate 93. At least 16 mafic dikes cut the Lynn Volcanics and Dedham Granodiorite along approximately 580 meters (1900 feet) of road cuts. See Skehan (1975) for a description of the general geology of the Pine Hill area, and Zarrow (1978) for a detailed account of the stratigraphy of the Lynn Volcanics and their relationship with the Dedham Granodiorite. The locations, attitudes, thicknesses, and dike types are shown on Figure 2. Dike 8 (Figure 2) is noteworthy in that it is a hyalo-monchiquite. This dike is described earlier in this report and its mode is shown on Table 1 (as is the Medford dike). The hyalo-monchiquite is darker in outcrop than is typical of the lamprophyres in the rest of New England (J.G. McHone, personal communication).

FIGURE 1. LOCATION MAP OF FIELD TRIP STOPS





KEY TO MAFIC DIKES

Dike No.	Width m	Width ft	Strike-Dip	Petrographic type
1	0.3	1.1	faulted	diabase
2	7.9	26.0	N85W-86N	dolerite, olivine
3	1.4	4.5	N83E-74N	diabase, bwn amph.
4	2.7	9.0	N82E-72N	dolerite
5	0.3	1.0	N15E-58E	diabase
6	3.4	11.0	N20E-77NW	dolerite
7	.03	0.1	vert. ±	diabase
8	0.4	1.4	N29E-90	hyalo-monchiquite
9	3.8	12.4	N49W-85SW	dolerite
10	0.2	0.6	N80E-90±	dolerite
11	6.7	22.0	N50W-82SW	diabase, bwn amph.
12	0.5	1.6	N50W-80NE	diabase
13	0.8	2.5	N53W-80NE	diabase, olivine
14	0.6	1.8	N72W-88N	dolerite
15	1.0	3.3	N74W-70NE	diabase, bwn amph.
16	0.4	1.4	N15W-73W	diabase
17	122	400	N15E-90	dolerite, biotite

FIGURE 2. Geologic sketch map of Pine Hill, Medford. Dedham Granodiorite (dg), Lynn Volcanics (lv), and Medford dike (TRmd) mapping after Wilson (1901). Road cut data by author.

The contact between the Lynn Volcanics and Dedham Granodiorite is exposed in the road cut between dikes 15 and 16 and is interpreted as an intrusive contact by Zarrow (1978). Note the thin diabase dike (16 on Fig. 2) nearly parallel to the roadcut. The Medford dike is exposed just beyond this dike.

Walk away from the highway at the flat area beyond the exposure of Medford and cross the downed portion of the cyclone fence and follow trail uphill into the reserve. This trail follows the axis of the Medford back to the parking lot. Note the numerous old quarry pits in the Medford dolerite. Side trips up onto Pine Hill and the tower to observe cross cutting dikes and the Boston Basin will be made if time permits.

0.3 Return via South Border Road into traffic circle and take exit northbound onto Rte 28 Fellsway West and proceed north on 28 parallel to Rte 93 to Stoneham.

3.9 Right (east) on Franklin St. in Stoneham.

6.0 Turn right (south) on Main St., Melrose and south to Lynn Fels Parkway.

6.2 Turn left (east) at Lynn Fels Parkway (easy to miss, Lynn Fels Pkwy has median divider). Proceed northeast 1.6 miles.

7.8 Turn right onto Main St., Saugus.

8.5 Take sharp right turn into K-Mart parking lot just short of overpass. Drive around right side of K-Mart and park behind store at curb on right along old quarry face. Stop 2 begins at north end of exposure.

STOP 2. DIKES CUTTING DEDHAM GRANODIORITE BEHIND K-MART: At least 13 dolerite and diabase dikes intrude Dedham Granodiorite at this locality. See Fig. 3 for locations, attitudes, and dike types. The dominant dike trend is northwest-southeast with a few dikes trending nearly east-west. The Dedham Granodiorite and dikes 6 and 7 have K-Ar ages of 600 m.y., 299 $\pm$ 21 m.y. and 383 $\pm$ 23 m.y. respectively (H. Krueger, personal communication, 1981). The chemistry of dike 7 is shown in Table 2 and its mode in Table 1. Dike 3 is offset by a SE-dipping fault containing slickensides trending N55-60°E. A thin , aphyric diabase dike is cut by the thicker aphyric dolerite and at the south end of the quarry (dikes 10 and 11 respectively, Figure 3).

Return to cars and leave parking lot via exit a north end. Take overpass over Rte 1 and turn left into northbound entrance to Rte 1 and proceed north on Rte 1.

9.9 Continue 0.1 miles beyond Lynn Fells Parkway overpass and park in large parking lot of Caruso's Diplomat restaurant just beyond gas station on right. Lock cars and walk back few hundred feet along Rte 1 and follow along highway side of river to spectacular

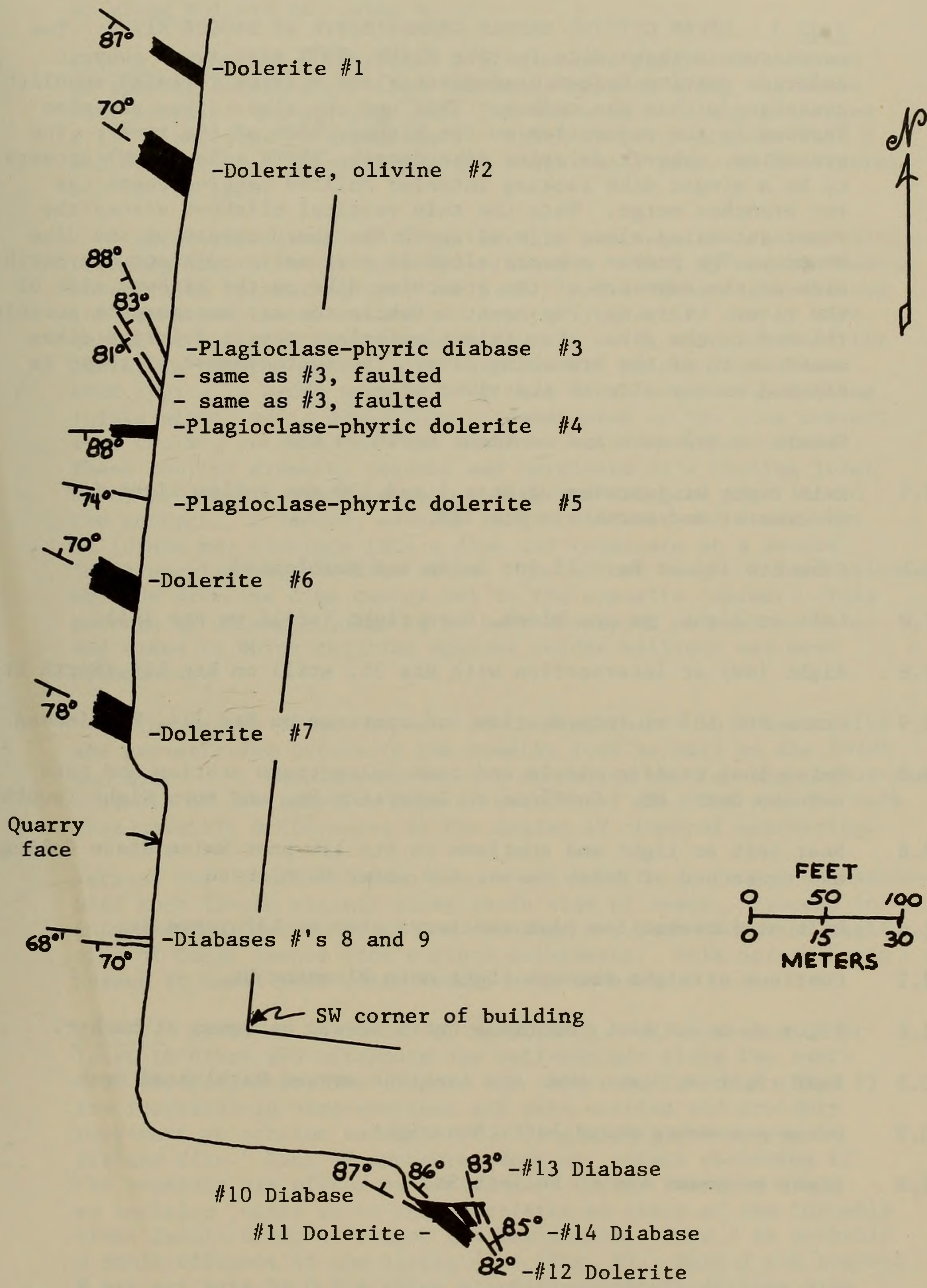


FIGURE 3. Geologic sketch map of mafic dikes intruded into Dedham Granodiorite behind K-Mart, Route 1, Saugus (STOP 2).

exposures on opposite side of the Saugus River.

STOP 3. DIKES CUTTING DEDHAM GRANODIORITE AT SAUGUS RIVER: The northernmost thick dike (strike N83°W, 85°S dip) is an aphyric dolerite cutting Dedham Granodiorite and a large foliated xenolith contained within the Dedham. This and the other dikes are also exposed in the excavation on the highway side of the river. The branching, aphyric dolerite dike (strike N57°E, dip 74°NW) appears to be a single dike lacking interior chilled margins where the two branches merge. Note the thin vertical offshoot across the river extending along a joint above the sharp corner of the dike branch. The Dedham appears slightly more mafic adjacent the north side of the exposure of the branching dike on the highway side of the river. This may represent a subtle contact metamorphic aureole related to the dike. Two thin plagioclase-phyric dolerite dikes occur south of the branching dike. The southernmost of these is exposed on our side of the river also.

Return to the cars and continue north on Rte 1.

12.9 Exit right at junction of Rtes 1 and 128 and follow signs for Gloucester and north via Rte 128.

16.4 Take Rte 114 at Exit 25 for Salem and Marblehead.

17.0 Left at light, go one block, turn right (still on Rte 114).

17.6 Right (SW) at intersection with Rte 35, still on Rte 114 (North St.).

18.9 Cross Rte 107 at intersection and continue on Rte 114, Marblehead.

19.2 Enter long traffic circle and pass Salem train station and take exit to Derby St. Continue to LaFayette St. and turn Right (south).

20.6 Bear left at light and continue on Rte 114 past Salem State College and cross end of Salem Harbor and enter Marblehead.

21.6 Left at intersection past cemetery, stay on LaFayette St.

22.2 Continue straight through light onto Pleasant St.

22.6 Right on Ocean Ave., continue until across causeway at harbor.

23.5 Bear right on Ocean Ave. and continue around Marblehead Neck.

23.9 Ocean Ave makes sharp left then right.

24.8 Right on Ocean Ave to Follett St.

25.0 Left on Follett Street to Chandler-Hovey Park. Park in lot or along Follett St. Stop 4.

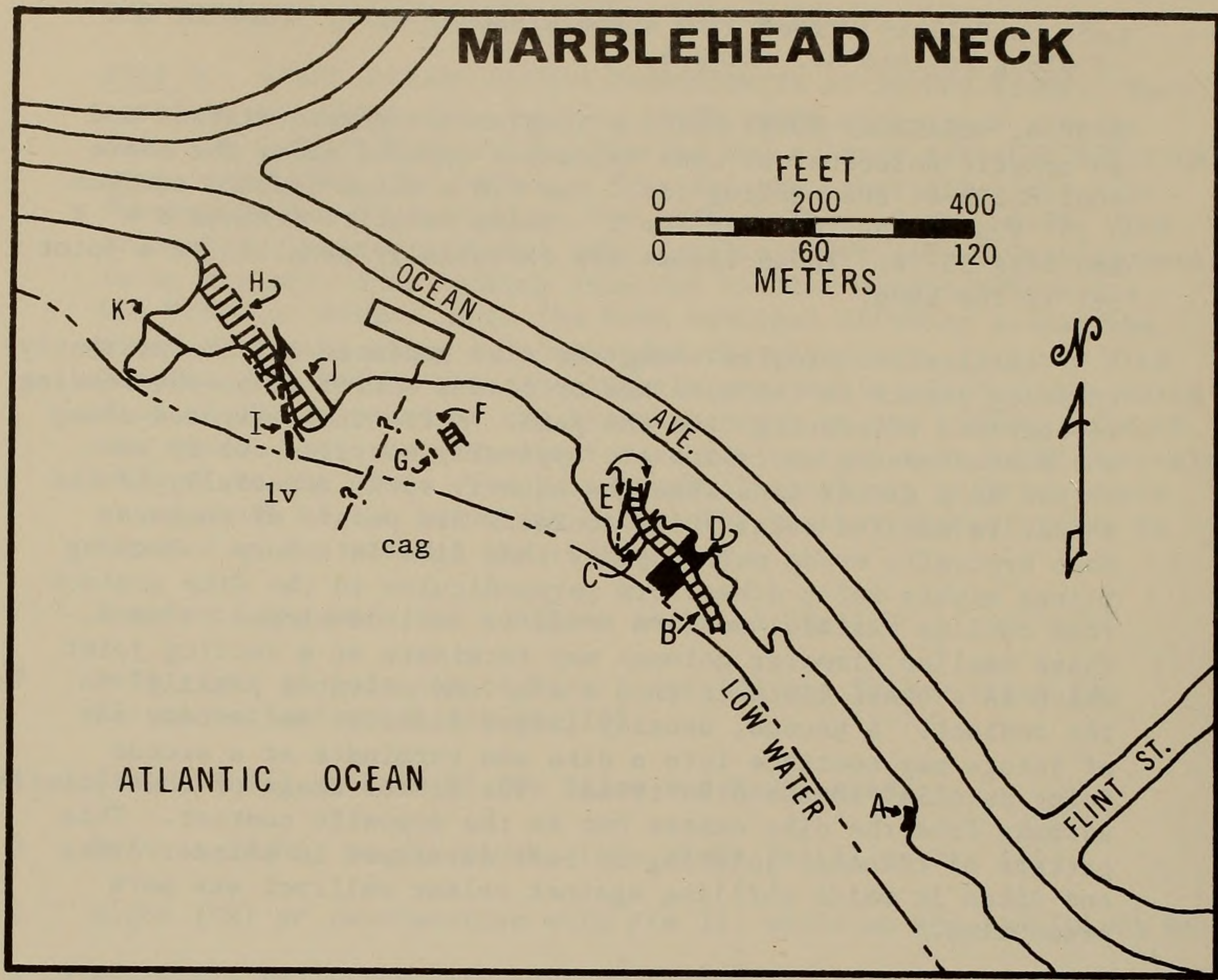
25.1 STOP 4. CHANDLER HOVEY PARK: A plagioclase-phyric diabase and an aphyric dolerite cut Lynn Volcanics exposed along the shore just north of the parking lot. The 4.8 m thick diabase strikes N 15° W and dips 70°W and the 1 thick dolerite strikes N 4° E and dips 55° E. These trends are essentially parallel to a joint set in the Lynn.

Accelerated erosion along the dike contacts and the northerly-trending joints in the Lynn has created a series of north-trending re-entrants retreating into the park. Mafic dikes exposed along the Massachusetts shoreline are typically quarried out by wave action at a faster rate than the country rock, especially if the latter is massive rock. Dike contacts are points of weakness that typically erode more rapidly than dike interiors. Cooling joints within mafic dikes form perpendicular to the dike contact (the cooling surface) to form crude to well-developed columns. These smaller diameter columns may terminate at a cooling joint which is a short distance into a dike and oriented parallel to the contact. A second, usually larger diameter and cruder set of joints may continue into a dike and terminate at a second joint parallel to the dike trend. The mirror image of this jointing extends from the dike center out to the opposite contact. This pattern of columnar jointing is best developed in thinner dikes and dikes in which chilling against colder wallrock was more pronounced.

The degree of development of cooling joints in a mafic dike and pre-existing joints in the country rock as well as the joint and dike trends relative the shoreline are far more important controls of the relative rate of erosion of dike and country rock than possible differences in the degree of chemical weathering.

Retrace our route to Ocean Avenue and back to south end of Marblehead Neck (beach visible along south side of road). Proceed to intersection just short of the causeway and park along the right side of Ocean Avenue (don't block driveways). Walk across Ocean Avenue to small park (with bench) near causeway.

26.7 STOP 5. DIKES AT SOUTH END OF MARBLEHEAD NECK: A series of at least 10 dikes and offshoots are well-exposed along the east-west trending shoreline (Figure 4). Dikes H, F, and B (Fig. 4) are identical in hand-specimen and thin section and probably represent en echelon segments of a single plagioclase-phyric diabase dike. Lack of exposures does not permit observing if the segments are offset by faulting or merely intruded along en enchelon joints as is characteristic of dikes of the Columbia River Basalt Group of Oregon and Washington. Dike J is probably a small offshoot of the larger dike (Fig. 4). Both J and segment H are cut here by 0.9 m thick plagioclase-phyric diabase dike trending N 9° E to N 20° W and dipping W to SW 40° to 65°. The southwest half of dike segment H and a thin aphyric dike farther



KEY TO MAFIC DIKES

Dike	Width m	Width ft	Dip	Petrographic type	Chemical type
A	2.5	8.1	80W-90	plagioclase-phyric diabase	=B?
B	6.0	19.8	86NE	plagioclase-phyric diabase	alkaline
C	1.2	3.9	68NW	diabase	
D	10.4	34.0	66NW	dolerite, olivine	tholeiite
E	0.7	2.2	81W±5	diabase	
F	7.3	24±1	84SW	plagioclase-phyric diabase	=B
G	0.6	2.0	65SW	diabase, rare plag. phenocrysts	
H	9.1	30.0	80NW	plagioclase-phyric diabase	=B
I	0.9	3.0	40W	plagioclase-phyric diabase	alkaline
J	1.8	1-6.0	vert.	plagioclase-phyric diabase	=B
K	0.3	1.0	vert.	diabase? no thin section	

FIGURE 4. Geologic map of mafic dikes intruded into Cape ann Granite (cag) and Lynn Volcanics (lv) at south end of Marblehead Neck (Stop 5).

out on the point (deep notch) have been deeply eroded. Chemical analyses of dikes B (H and F), D, and I are listed in Table 2 and modal analyses are shown in Table 1.

The dikes within the park have intruded Lynn Volcanics but exposures to the east along the beach are in what appears to be Cape Ann Granite according to Skehan (1975). The contact between Lynn and Cape Ann is covered by the beach and riprap but must lie approximately where shown on Figure 4. At low tide the exposures to the east can be reached by the beach and, at high tide, via the sidewalk along Ocean Avenue.

Dike B (= H and F) cuts two aphyric dolerite dikes (D and E, Fig. 4) and a thin, aphyric diabase dike (C). Xenoliths of granite are present within the dike. A large, foliated biotite granulite (Skehan, 1975) can be seen within the Cape Ann Granite at locality F and is cut by dikes B and D as well. Dike D is tholeiitic in contrast to dikes B and I which are alkaline (Table 2). Approximately 120 m farther east from dike B a plagioclase-phyric diabase dike is present and is somewhat less altered than either dikes B or I. Definite correlation with either will require a chemical analysis but it is tentatively considered equivalent to B.

It is clear from cross cutting relationships, petrography, and chemical compositions that at least 4 episodes of mafic dike intrusion are represented here. Two sets of alkaline, north to northwest-trending plagioclase-phyric diabase dikes post-date a tholeiitic, northeast-trending, aphyric dolerite dike and two NE-trending, aphyric diabase dikes.

Retrace our same route all the way back through Salem to Rte. 128.

33.8 Turn north on Rte. 128 at Exit 25 toward Gloucester and Rockport.

38.5 100 feet north beyond the exit from the Howard Johnson service area a northeast-trending mafic dike exhibiting well-developed columnar jointing perpendicular to contacts is exposed on right.

57.2 Park right in breakdown lane at bottom of long hill just before Exit 10 in Gloucester. Walk across Rte 128 to large roadcut.

STOP 6. DIKE AND XENOLITHS IN CAPE ANN GRANITE: The xenoliths are gabbro porphyry with labradorite phenocrysts (Dennen, 1976), suggesting the presence of a mafic pluton somehwere at depth beneath Cape Ann.

Note a 42 cm thick, plagioclase-phyric dolerite dike trending N 30° E and dipping 60° NW.

Turn left at Exit 10 onto Rte. 127 and drive north to Rockport.

59.9 Continue straight at "Five Corners" intersection onto Broadway.

60.3 Turn right at Rte 127A (South Street), two blocks and LEFT on Norwood Avenue for three blocks then left on Highland Ave. and park on right. Walk down hill on Highland Ave. to asphalt path to right. Follow path out to Rockport Headlands and Stop 7.

STOP 7. PLAGIOCLASE MEGACRYST-RICH DIKE AT ROCKPORT HEADLANDS: This is one of the most unique diabase dikes in eastern Massachusetts, if not New England. Modal and chemical analyses are listed in Tables 1 and 2 respectively. The dike contains abundant plagioclase megacrysts up to at least 9.2 cm in length which increase in abundance and average size toward the interior of the dike where they account for approximately 35% (megascopic estimate) of the rock volume. In thin section, the center of the dike contains 53.1 volume percent plagioclase phenocrysts and megacrysts (Table 1). The grains are relatively fresh with some cores severely saussuritized and sericitized. A prominant joint occurs about 35 cm in from the east contact in parallel to it. Plagioclase phenocrysts up to 15 mm long make up less than 5 to 10 percent of the volume of the chilled zone bounded by this joint and the dike contact. About 50 cm farther into the dike a second prominant joint is present and parallel to the dike trend. The rock between these two joints is courser with phenocrysts up to about 27 mm accounting for 10 to 20 percent of the rock. From here inward, megacryst size and abundance increase to the maximums at the dike's center mentioned above. This distribution of megacrysts and phenocrysts is in agreement with that expected to be produced by flowage differentiation.

The dike strikes N 14° W and dips 88° E here and is also exposed below the parking lot at the end of Bearskin Neck across Rockport Harbor. Note this is an apparent left-lateral offset and one could hypothesize a fault trending through the harbor but such evidence is shaky at best without a visible fault. The dike can also be seen in the distance across Sandy Bay in Pigeon Cove where it is 8 m thick, trends N 27° W and dips 74° E. This locality is also slightly offset to the west from the more southern exposures.

A 6.0 cm thick aphanitic mafic dike cuts the megacryst-rich diabase near the water's edge. The large relatively smooth surface on the granite a few meters to the west was produced by erosion stripping of this thin dike.

End of field trip. Return south to Route 128 for connections north and south. A scenic route around Cape Ann via Rte. 127 also returns to Rte. 128 (7.7 miles) if you have time.